ACKNOWLEDGEMENT

Alhamdulillah. For His guidance and blessing, undertaking this Ph.D. has been a truly life-changing experience and it would not have been possible to do without the support and guidance that I received from many people. I would like to acknowledge the USM for giving me a chance to experience lifetime opportunities and to be able to come out with this thesis. I would like to first say a very big thank you and deepest gratitude and appreciation to my supervisor, Prof. Dr. Ismail Abustan, his wide knowledge and effort, in guiding me through this research, for his patience, motivations, and encouragement.

Thank you for my co-supervisor, Dr. Mohd Remy Rozainy Mohd Arif, his advice had inspired me in many ways. I gratefully acknowledge the funding received towards my Ph.D. from the UNIMAP under Ph.D. fellowship schemes SLAB. Thanks to P.M Dr. Khairul Nizar Ismail for his encouragement and supervisory role and also Dr. Mahyun Ab Wahab for his valuable input.

I am also grateful for the funding received through JPA Malaysia. My sincere thanks to the assistant engineers who gave access to the laboratory as well as guided me through the laboratory work. Their precious support made me possible to perform this research I am indebted to all my friends in PPKA's who were always so helpful in numerous ways. I would also like to say a heartfelt thank you to my Dad for his financial support, Mom and Ana for always encouraging me to follow my dreams. To my small family for helping in whatever way they could during this challenging period. And finally to Rohaidzat, who has been by my side throughout this Ph.D., and to my Maryam Elle
for being such a good little baby, and making it possible for me to complete what I started.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

LIST OF ABBREVIATION

2D	Two-dimensional
3D	Three - dimensional

RANS	Reynolds averaged Navier-Stokes equations
ADV	Acoustic Doppler Velocimeter
CFD	Computational Fluid Dynamic
PIV	Particle image velocimetry
VOF	Volume of fluid
TKE	Turbulence kinetic energy

LIST OF SYMBOLS

V	Velocity (m/s)
n	Manning’s coefficient

R	Hydraulic radius (m)
S	Bed Slope (º)
g	Gravitational acceleration (m/s^2)
f	Weisbach resistance coefficient
Q	Flow discharge (m^3/s)
A	Cross sectional area (m^2)
P	Wetted perimeter (m)
s’	Porous thickness (m)
h’	Height over porous thickness (m)
B	Flume width (m)
Re	Reynolds number
Fr	Froude number
U*	Friction velocity (m/s)
y	Distance from porous bed (m)
h	Total flow height (m)
U/Uin	Dimensionless velocity X- dimension
Z/Uin	Dimensionless velocity Z – dimension
k	Turbulence Kinetic Energy (m^2/s^2)
x, y, z	Cartesian coordinate (streamwise, bottom normal, transverse) velocity component (m/s)
U_0	(Streamwise) slip velocity at the interface level (y = 0) (m/s)
U_p	(Bulk) or superficial seepage velocity (m)

Hp	Thickness of the subsurface layer, or average height of porous bed (m)
s'/h	relative porous thickness

CORAK ALIRAN AIR DAN CIRI-CIRI HIDRAULIK HEKSAGONAL MODULAR SEBAGAI DASAR KEPADA SALIRAN

ABSTRAK

Kajian telah menunjukkan bahawa reka bentuk yang mampan seperti Sistem Saliran Lestari (SUDS) akan membantu mengurangkan kesan-kesan ini. SUDS adalah sistem saliran semulajadi yang mensimulasikan saliran semula jadi dari tadahan dan berfungsi dengan harmoni untuk mencapai peningkatan dalam penyusupan tanah dan air larian; dan pengurangan kadar air aliran dari permukaan, meningkatkan biodiversiti dan akhirnya meningkatkan kemampanan sekitaran. Walau bagaimanapun, kelestarian peranti SUDS dipersoalkan kerana bahagian komponen melibatkan penggunaan sumber semula jadi. Kajian ini mencadangkan aplikasi yang baru direka iaitu Sistem Saliran Hijau (GDS) menggunakan Heksagonal Modular (HM) sebagai asas permukaan. Oleh itu, adalah penting untuk menentukan ciri hidraulik modul ini yang memberi tumpuan kepada HM. Tesis ini secara eksperimen menggunakan saluran air buatan dan rig simulator. HM sebagai asas permukaan di tiga cerun berbeza 0.002, 0.005 dan 0.008 dan setiap cerun terdiri daripada empat halaju air yang berbeza. Untuk mengesahkan hasil pengukuran percubaan saluran air buatan, pemodelan berangka untuk semua kes telah dipertimbangkan, di bawah keadaan operasi yang sama dengan pengukuran eksperimen menggunakan model media berliang dan model pegolakan (FLOW3D). Keputusan eksperimen mendapati bahawa keputusan eksperimen dan pemodelan menujukkan keputusan yang setara. . Halaju aliran maksimum berlaku berhampiran permukaan air dengan peningkatan kelajuan aliran pada kedalaman yang semakin meningkat. Cerun yang curam menunjukkan halaju air maksimum yang lebih tinggi berhampiran permukaan air yang ditekankan ke arah akhir saluran. HM sebagai asas permukaan berliang pada ciri-

ciri aliran dalam saluran terbuka adalah berbeza berbanding dengan katil yang tidak dapat ditembusi. Halaju dikurangkan dengan penurunan paras air disebabkan oleh pengaruh HM pada aliran di atas asas permukaan berliang. Adalah jelas bahawa urutan pengurangan halaju poros dengan HM> asas permukaan tanpa HM > asas yang tidak dapat ditembusi.

FLOW PATTERN AND HYDRAULIC CHARACTERISTICS A OF HEXAGONAL MODULAR AS CHANNEL BED

ABSTRACT

Studies have shown that sustainable designs such as Sustainable Drainage Systems (SUDS) would help mitigate some of these effects sustainable. SUDS is natural drainage systems that simulate the natural drainage of a catchment and work in harmony to achieve an increase in ground infiltration and treatment of runoff; and a reduction in flow rates and volume of surface runoff, improving biodiversity and ultimately improving sustainability. However, the sustainability of SUDS devices is questionable because their component parts involve the use of natural resources. This study proposed the application newly designed namely Green Drainage System (GDS) using HM as channel bed. Therefore, it is important to determine the hydraulic characteristic of this module focusing on HM. This thesis investigated experimentally using tilting flume channel and rig simulator. HM as a bed channel was tested at three different slopes of 0.002, 0.005 and 0.008 and each slope consists of four different discharges. In order to verify the results of experimental measurements of the flume channel, the numerical modeling for all the cases was considered, under the same operating conditions with experimental measurements using porous media models and turbulence model (FLOW3D). Results agreed that the experimental and numerical results show good agreement. The maximum flow velocity occurs near the water surface with an increasing flow velocity at increasing depth. The steeper the slopes shows higher maximum water velocity near the water surface emphasized toward the end of flume channel. HM as the effect of porous bed on the turbulent characteristics of the flow in an open channel is different in comparison with the impermeable bed. The velocities are reduced with the decreasing of the water level due to the greater influence of the HM on the flow above the porous bed. It is apparent that the order of reduction velocity porous bed with HM >porous bed without HM > impermeable bed.

CHAPTER ONE
INTRODUCTION

1.1 Background

In the world of today, there is an ever-increasing urbanization. Urbanization alters the natural hydrology of a catchment. It increases the proportion of impervious areas through the construction of buildings, roads, and other impermeable surfaces. The increase in the percentage of impervious areas reduces the ability of the catchment surface to retain water through infiltration and other hydrological losses such as vegetation interception, evapotranspiration and depression storage. Figure 1.1 illustrates how increasing the impervious area of a catchment through urbanization increases the volume of stormwater runoff.

The atmosphere is changing, delivering an expanded recurrence of extraordinary climate contrasted with what could be experienced just 20 or so years back. The combination of these two changing components are making issues in urban regions, particularly if respect is taken to outrageous precipitation. The obsolete underground sewer framework is encountering limit issues. There are in many case unable of handling the increased runoff resulting from larger rainfall quantities and more impermeable surface area than they were originally designed for. This has led to a fairly new approach within urban drainage, where the need of bypassing and expanding the existing drainage systems has emerged (DID, 2012). This has led to the use of what is often referred to as Sustainable Urban Drainage Systems, (SUDS), where the stormwater is conveyed and infiltrated on the surface rather than in concrete channel. This has led to a division in the scientific areas within urban drainage, where the hydraulics has dominated the pipe systems and hydrology has dominated the concrete drainage system systems. While hydrology is a major factor in sustainable urban drainage, ever-increasing flooding events show that the hydraulic field cannot be disregarded. The size of floods and their path of conveyance are often erratic and can potentially cause extensive damage to infrastructure. It is therefore important to understand how open flow hydraulics act in urban environments. There have developed advanced hydraulic methods for dealing with overland flow in recent years, in order to assess the flooding impact in urban areas. These methods are to a large extent purely hydraulic. There are very limited extent be able to model the hydraulic response through channels where infiltration is also present, for example, swales and grassed filter strips. The result of this model shows a clear knowledge gap within the hydraulic field in overland urban drainage. In this thesis, an attempt to bridge this gap is made by establishing a model that is capable of conveying the runoff and the hydraulics of overland flow in a drainage system. This model consists of a hydraulic capable of modeling unsteady channel flow for varying conditions, as would be expected in an urban area.

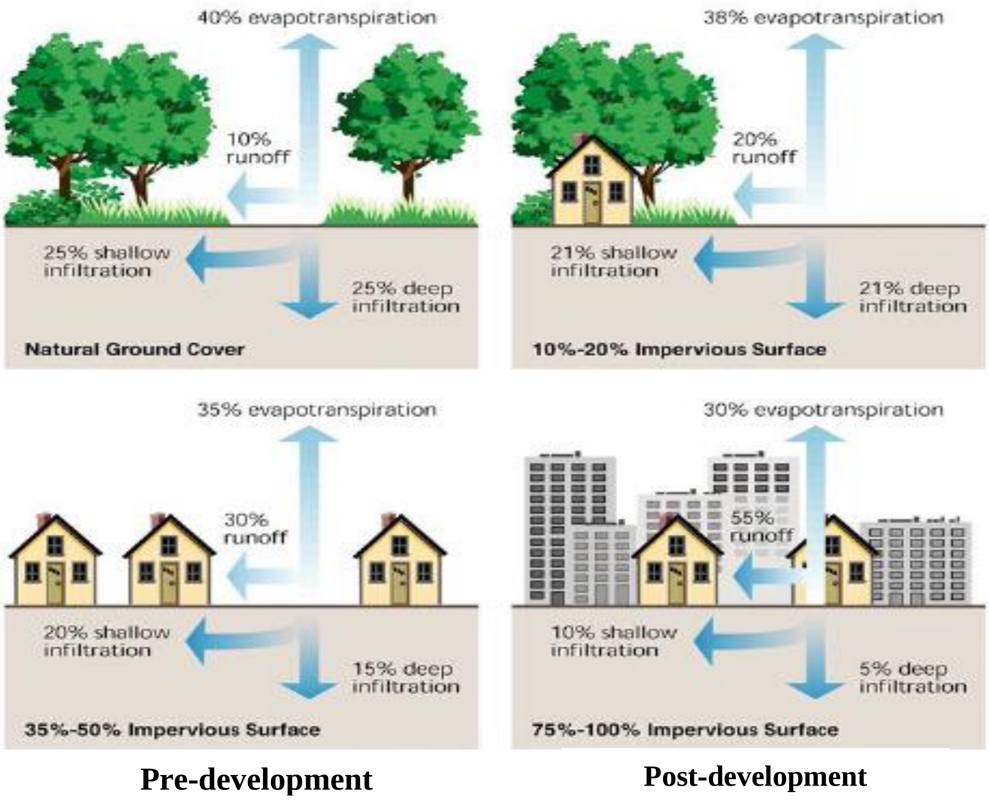

Figure 1.1: The effect of urbanization and increasing impermeable surfaces on the volume of infiltration, runoff, and evapotranspiration (FIRSWG, 2001)

1.1. The need for Sustainable Drainage

Rapid disposal, localized, reactive and mono-functional drainage concepts have been widely practiced in Malaysia. The traditional approach that is widely practiced in Malaysia allows developers to put in drains where appropriate. In Malaysia in order to maximize housing density, developers normally channel all drainage to one or large trunk drains. All drains to trunk drains are normally concrete-lined and of the open channel, type to minimize the land area required. Previously, in Malaysia, urban drainage practice has been largely based on 1975 DID Urban Drainage Design Manual that covers essentially the planning, basis of design, flood discharge, hydraulic design of open channels, structures, storm drainage for urban streets, detention storage, erosion and sediment control and information to be submitted with design. The rational peak discharge estimation method has been substantively used, even for large and complex hydraulic structure in a large catchment. As a result, cost-effective design and construction have seldom been realized. Widening and channeling rivers and drain to cater for increased discharges as the urban area develops is inherently defective from the environmental point of view. As the urban areas continue to expand in all towns in Malaysia the demand will continue to increase. The Department of Irrigation and Drainage (DID) has estimated more than RM 10 billion to mitigate the current existing flood problem (DID, 2012). If the country continues to urbanize, the flood problem will continue to increase (Intan Baizurah, 2014).

Sustainable Urban Drainage System (SUDS) has been implemented in the United Kingdom which related with the stormwater management concept. Other countries such as the United States and Australia carry out the similar concept with different names. It is called Low Impact Development (LID) in the United States and Water Sensitive Urban Design (WSUD) in Australia. In 2002, the Malaysia government under DID introduced same practices and has officially approved urbanization water management or the Manual Saliran Mesra Alam (MSMA) to be used to regulate development works and to assist relevant parties towards achieving sustainable storm water management (Ghani et al., 2012). The main focus of MSMA is to manage the stormwater instead of draining it away as fast as possible to a more environmentally approach known as control as source approach. This approach utilizes detention/retention, infiltration, and purification process. The quality and quantity of the runoff from developing area can be maintained to be the same as a pre-development condition from the aspect of quantity and quality runoff also known as uncontaminated zero contribution to the peak discharge (Intan Baizurah, 2014).

New approach drainage module which is called Green Drainage System (GDS) has been designed in order to imitate the concept of MSMA and SUDS management control which shifted the traditional concept of drainage engineering practices based on rapid disposal towards this new concept. Table 1.1 shows the components of GDS which are overlaid by a layer of sand and aggregates at the bottom part, followed by porous media which is called as a Hexagonal Modular (HM) (Figure 1.2). The HM is arranged as interlocking with one and another as far as looking from top view look alike beehive structure.

Table 1.1: Components of GDS

Components	Specification	Details
HM	Shape	Hexagonal
	Dimensions	Height : 100 mm Diameter : 100 mm Wall Thickness : 5mm
	Compressive strength	72 kN
	Material	PVC
Clean River Sand		Mean size between 0.5 mm to 2.0mm
Aggregates		Mean size between 1.5 mm to 3.0 mm

Figure 1.2: Hexagonal Modular (HM)

1.2. Problem Statement

Progressive movement from agriculture to an industrialized economy has shifted the population into urban centers. In 1970, a total of 26.8 % of the population were urban dwellers. By 1980 urbanization had increased the population to 35.8 % and by 1991 to 50.7%. Recent projection indicated that urbanization in Malaysia would result in an urban population exceeding 65% by the year 2020 (Baizurah, 2014). Rainfall-runoff has been challenging in the built environment ever since the emergence of an urban population and the infrastructure required supporting such a population. The challenge is increasing with the growth of urban population not only locally but of the world. Communities are growing and indelibly changing the landscape. Forests, farms, and meadows are being transformed into houses, shopping centers, roadways and parking lots, which all have a common hydraulic property which is a modification of rainfall-runoff quantity and quality processes through imperviousness. The normal practice of constructed urban and highway environments which were designed for the rapid and efficient transport of stormwater flows increased localized flooding. The highly impervious nature, relative lack of roughness and reduced hydraulic resistance of our urban pavement and surface/subsurface drainage systems have resulted in increased urban rainfall-runoff peak flows, increased flow volumes and reduced lag time as commented by Davis (2014).

Records from 1980 to 2016 rainfall data have shown a trend towards higher rainfall intensities and an increasing frequency of high-intensity rain events. In addition, climate change effects of sea level rise and increases in rainfall intensities make it necessary for drainage infrastructure to be upgraded and drainage requirements to be raised in order to protect developments from the flood. The approach of the new system is designed to meet MSMA and SUDS policy, however, the characteristics of hydraulic and effectiveness conveyor of GDS raised questions about how efficient the system works, including capability of GDS to cater runoff, flow patterns, its roughness coefficient and efficiency rate of filtration despite physically demonstrated but never been experimental tested. By knowing the hydraulic performances of the GDS system, one may resolve experience issues of the framework in designing the new module and as well as helping in reducing the degree of imperviousness.

1.3. Scope of Study

This research has specific scope and limitation. The scope of this research can be a list out as**:**

1) This study is based on experimental data and numerical modeling and measured in an infiltration rig and in a laboratory flume using four sets of the test condition.
2) The rate of infiltration in the porous bed is affected by the structure of the different types of layers in the system. Since this study is primarily concerned with estimating total infiltration, rather than understanding the dynamics of evaporation, infiltrative processes are investigated at the macro scale. This approach focuses on estimating the rate of filtration based on an empirically-derived relationship between infiltrative water losses without modeling outer heat in detail.
3) Water velocity profile and mean velocity profile were obtained by using four different set of conditions. The GDS module was tested by laboratory experiment using flume.
4) The water flow and bed slope of the channel were controlled in the test. Hydraulic parameters such as water velocity and water depth data were collected.
5) Hydraulic parameters obtained were analyzed using Manning's equation. Manning's coefficient of the various bed channel conditions were calculated from the Manning's equation. Included in this study are data that provide support for both the assumption of a constant *n* and use of a predictive equation for a varying n within the same channel lined with uniform roughness depending on the parameters of the flow condition in the channel.

6) For this study, 5 mm sizes of meshes were created so that it can pick-up the GDS.
7) The refinement of each section was done conserving an aspect ratio, of less than 2 and an adjacent cell size ratio of less than 1.25 in all three directions (x-y, x-z, y-z) as specified by the FLOW-3D User Manual to minimize errors and increase the stability of the model.

1.6 Research Objective

This thesis has four primary objectives which are :

I. to examine the flow velocity profiles of HM on drainage bed
II. to study the influence of HM as porous bed on surface a drainage bed
III. to determine Manning's roughness coefficient of hexagonal modular (HM) as a porous channel bed.
IV. to predict the hydraulic performance of GDS using computational model (FLOW3D)

CHAPTER TWO
LITERATURE REVIEW

2.1. Research Background

Urbanisation and development have led to an increase in impermeable surfaces and lead to a drastic reduction in natural infiltration of rainwater, thereby causing an increases in the volume of surface runoff to more than 80% of the total rainfall volume. This growing urbanization reduces the soil absorption capacity and storage of stormwater, and , together with the ageing of the existing drainage infrastructure shows led to an increase in the cost of flood management (Wegehenkel and Kersebaum, 2008; Einfalt et al., (2009); Tingsanchali, 2012; Makropoulosetal , 2008).

Runoff flow rate has increased significantly thereby causing erosion of unsealed ground, flooding, and pollution of water resources. A new site or catchment area can become impermeable due to developments (parking lots, roofs, pavements and roads) and natural infiltration becomes difficult, even available pervious ground cannot carry out infiltration normally, due to soil compaction and stripping of topsoil during construction (CIRIA C523, 2001). Further, paved surfaces have left little or no room for green infrastructures (GI) such as parks and other vegetated areas (Haase, 1986). As a result of these impacts, water bodies such as streams and rivers have to cope with larger volumes of stormwater than they would normally handle, hence constructed or lined drainage systems are applied to reduce the risk of flooding, water logging, subsidence and stagnant pools. These conventional drainage systems consist of drains, kerbs and gullies.

However, as the components of conventional drainage systems are designed to work independently of each other, they end up producing heterogeneous waste streams which make recovery of resources difficult and expensive and could end up polluting water bodies (Butler and Davies, 2004). As a result, a more integrated approach to drainage is needed whereby drainage components interact with each other thereby reducing water pollution and flooding (Adams and Papa, 2000; Brown, 2005).

2.2. Conventional Drainage Systems

Urban drainage systems drain two types of water, wastewater, and stormwater. Wastewater is the outcome of water used in everyday life and industrial use. It carries particles and chemicals which could cause pollution and create health risks. Stormwater is any form of precipitation that has fallen on a built-up area and which, if not properly drained, could result in flooding. Conventional drainage systems consist of either combined sewers or separate sewers. Combined sewer systems convey both sewage and surface runoff through a single pipe to sewage treatment plants, which when overloaded, especially in periods of heavy rainfall, are allowed to overflow into water courses (USEPA, 2012a). In dry weather, the pipes convey mainly wastewater but during periods of rainfall, stormwater is added to the flow which can easily overwhelm the sewage treatment plants (Bell, 2011).

In separate sewer systems, such as Malaysia, surface runoff and sewage are conveyed in separate pipes usually laid side by side, the former to water courses and the latter to treatment plants. Separate sewer systems may seem better compared to the combined sewer system however, this may not be so because surface runoff becomes contaminated with pollutants such as oil, dust, organic matter, silt, nutrients, eroded soil particles and chemicals such as detergent and pesticides; which is then dumped directly into receiving water bodies. Further, there is the issue of cost when compared to combined sewer systems, due to the additional pipe and wider excavations required to accommodate both pipes (Pyzoha, 1994; CIRIA, 2001; Butler and Davies, 2004).

2.3. Problems associated with conventional drainage systems

The approach of conventional drainage systems to stormwater management focuses mainly on water quantity, much less on water quality and with little consideration for biodiversity value, such as landscaping potentials and recreational opportunities. This means that the system focuses more on transporting stormwater as quickly as possible away from its source so as to prevent flooding, without considering pollutant concentration and its resultant effects on aquatic habitats and biodiversity. This method of conveying stormwater also ensures that infiltration of surface runoff is decreased thereby reducing groundwater recharge which leads to lowering of the groundwater table, and depletion of groundwater can lead to water shortages and soil subsidence (CIRIA 522, 2000; Charlesworth, 2010).

The failure of existing systems to cope with runoff due to most of them exceeding their capacity has also led to an increase in wastewater flowing into water courses causing water bodies, such as streams and rivers, to swell and overflow their banks leading to flooding and erosion of aquatic habitats. Erosion causes the deposition of silt and sediments downstream where water flow is slower, further damaging aquatic habitats leading to loss of amenity and wildlife (CIRIA C523, 2001; Butler and Davies, 2004; Hoyer et al., 2011).

The various components of conventional drainage systems (sewerage system, wastewater treatment plants and receiving water bodies) have been designed to operate in such a way that each component meets the needs of its users, including the environment. However, because they are designed to work independently with little or no interaction between components (Butler and Schütze, 2005), they eventually produce heterogeneous waste streams which makes recovery of resources (such as water) difficult and treatment more complex as a higher level of expertise, energy, space and cost is required, thereby making treatment unsustainable (Balkema et al., 2002). Another major shortcoming of the conventional drainage system is the sustainability of materials used in their construction which include clay, iron, concrete or plastic for pipes, and aggregates for constructing pipe surrounds and pavements (WRAP, 2011). The extraction of gravel, an aggregate used in concrete production for concrete pipes, has a significant impact on the environment in terms of depletion of gravel deposits, dust pollution, poor visibility, increased soil erosion, silting up and pollution of water bodies (Paige-Green and Hongve, 2003) In handling these problems, CIRIA C523 (2001) proposed two alternatives namely:

a) improvements in conventional drainage systems

b) engineering practices sustainable urban drainage.

In reality, these two approaches should be considered together rather than separately. Improvements in conventional drainage systems and engineering practices include construction of flood defences. In addressing these problems associated with conventional drainage systems, Andoh (1994) proposed the separation of stormwater from wastewater and suggested that distributed systems provided an alternative preventative approach to urban drainage at reduced costs compared to conventional drainage systems. This alternative approach recommended the use of stormwater management techniques and/or natural drainage patterns as an option to the use of pipes in conveying stormwater (Butler and Davies, 2004). Neilson (1999) and Joos et al. (2007) also supported the decentralised approach to urban drainage suggested by Andoh (1994).

2.4. Sustainable Drainage Systems

SUDS, rather than trying to modify nature, work in harmony with it by reducing the flow rate, peak flow and volume of surface runoff. SUDS, in most cases, simulate the natural drainage of a site/catchment thereby reducing the amount of runoff flowing into sewers, reducing erosion, improving the quality of surface runoff by treating pollutants, improving quality of water bodies, recharging groundwater and improving biodiversity (Casal-Campos et al., 2011). SUDS are devices that give equal consideration to water quantity, water quality and public amenity or biodiversity (Figure 2.1) in contrast to conventional drainage systems and these three components are integrated, working together to reduce flood risk and pollution as well as improving the environment. SUDS do not function in isolation but as an integrated system and can either be used in conjunction with conventional drainage systems or other SUDS systems (Dickie et al., 2010).

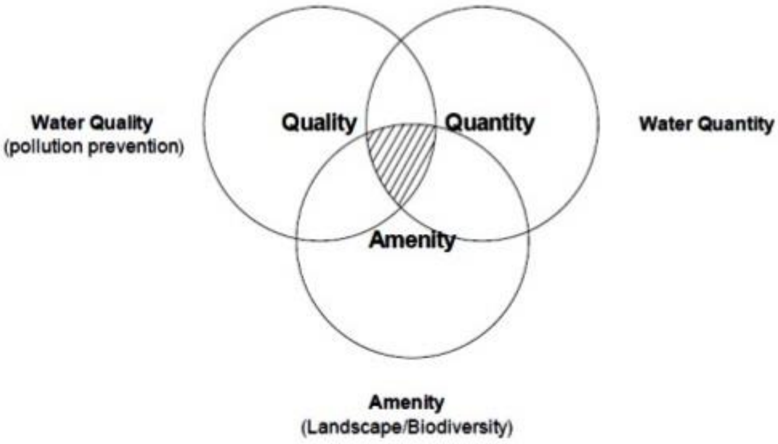

Figure 2.1: Three-ringed circus model for SUDs (Apostolaki et al, 2005)

SUDS have been widely and successfully used in USA, Europe, Australia and Japan (Ghani et al., 2008) and their benefits are summarised below:

a. SUDS help to identify and control flooding and pollution at source thereby encouraging easier prevention or containment measures, locally.
b. As SUDS provide natural attenuation and temporary storage of surface runoff, flood risk is reduced in a catchment area and further downstream.
c. Surface water retention in a development helps to recharge groundwater and maintain its balance by infiltration thereby preventing low river flows especially in summer periods.
d. Stormwater treated by SUDS can be harvested and re-used for domestic uses such as toilet flushing and gardening.
e. SUDS help to recharge groundwater and thereby maintaining natural vegetation.
f. SUDS reduce the need and cost to enlarge and upgrade existing sewers to accommodate runoff.

g. Runoff storage areas can serve as landscaping or amenity areas (CIRIA C523, 2001).

2.5. Types of Sustainable Drainage Systems

There are several SUDS devices and each one is designed to fulfill the three objectives of sustainable drainage as described in Figure 2.2. They manage surface water by processes of attenuation, infiltration, and detention, and each device can be applied in a sequence such that it mimics the natural drainage of a site before development (Woods-Ballard et al., 2007). According to Woods-Ballard et al. (2007), SUDS devices are grouped into four main techniques:

a) permeable surfaces and filter drain,

b) infiltration devices,

c) basins, ponds and wetlands and

d) filter strips and swales.

2.5.1. Permeable Surface and Filter Drain

Permeable surfaces are designed to allow surface water drain from permeable paved surfaces to the sub-base (layer below the surface) faster than rainfall intensity so as to prevent flooding (Coupe et al. 2006b; Woods-Ballard et al., 2007), and are therefore necessary for stormwater management (Gomez-Ullate et al., 2011). The sub-base is of the open-grade type which means that comprised of large aggregate spaces which are porous to allow the infiltration of water into the ground, into an underground storage or into the next SUDS management stage, depending on the permeability of the existing ground/soil. Permeable surfaces include permeable block paving, porous asphalt, reinforced grass and gravel (Shaffer et al., 2009).

The permeability surrounding soil is vital as this will determine what type of sub-base to be installed. Permeable soils will allow total infiltration of treated water into the ground and therefore does not need to be diverted into other drainage systems such as sewers or watercourses. Semi-permeable soils allow the partial infiltration of water and a fixed amount of water is allowed to infiltrate into the ground and excess water is drained via a series of perforated pipes into storage tanks or other drainage devices. Impermeable soils will not allow the infiltration of water and hence the sub-base is lined with impermeable flexible membranes to capture water and divert it into other drainage devices, a method which is also currently applied to contaminated sites to prevent contamination of groundwater (Interpave, 2006; Interpave, 2008). The sub-base filters out particles and sediments and organic matter are reduced by microorganisms present on the sub-base surface materials, unlike conventional drainage surfaces such as concrete pavements, which convey surface water quickly to overloaded drains and water courses through pipes, thereby leading to water pollution and flooding. Permeable surfaces are inclined to stopping up by stormwater sediments which could influence infiltration rates and water quality (Siriwardene et al., 2007) but unlike conventional piped systems for which underground inspection required, clogging of permeable surfaces can easily be identified and rectified with visual inspection (Woods-Ballard et al., 2007; Interpave, 2008; Shaffer et al., 2009).

Permeable surfaces include permeable block paving, porous asphalt, reinforced grass and gravel systems, and gravel (Shaffer et al., 2009). Studies by Brattebo and Booth (2003) and Gomez-Ullate et al. (2011) showed that water storage by these surfaces was not significantly different and, according to Brattebo and Booth (2003), water quality was significantly better than impermeable surfaces.

2.5.2. Sustainability of SUDS components

Criteria for measuring sustainability in SUDS include life-cycle costs (Ellis et al., 2004; Ellis, Lundy and Revitt, 2011) and catchment dynamics (Scholz, 2006) which includes rainfall and infiltration characteristics, runoff quality and flood protection (Kellagher and Udale-Clarke, 2008). However, sustainability in SUDS should not only be limited to costs, water conservation, and water quality alone but also to its overall structure and components. When considering the sustainability of materials employed in the construction of SUDS devices, SUDS components may be as unsustainable as components of conventional drainage systems (Shaffer et al., 2009). In fact, SUDS may actually have more significant environmental impacts (e.g. resource depletion, release of emission and waste generation), social impacts (e.g. noise pollution and traffic associated with transportation of materials) and economic impacts (e.g. cost implications of consumption of water and energy), compared to conventional drainage systems (Shaffer et al., 2009; WRAP 2010). This is because SUDS devices sometimes require slightly more materials in their construction (e.g. the sub-base of permeable pavements) compared to conventional systems, and this involves the utilization of more natural resources thereby increasing unsustainability. For example, the use of thicker sub-bases in SUDS required for water storage implies that more aggregates are needed and larger volumes of soil excavated and transported for disposal or re-used elsewhere thereby increasing their overall environmental impact compared to conventional drainage systems (Shaffer et al., 2009). Also “hard” materials such as concrete and gravel used in SUDS are similar to materials used in conventional drainage systems and therefore the impact of the manufacture and transportation of these materials on the environment, from source to site, may also be similar in both systems (Shaffer et al., 2009).

2.6 Porous bed

Some subdisciplines, such as hydrology, ecology, sedimentology and hydraulic engin eering, share an interest in predicting the flow of a turbulent stream. In principle, prediction of flow through a porous bed is a prerequisite or core condition for predicting the complex problem of diffusing and dispersing active and passive contaminants in permeable streams.

The understanding of the involved phenomena is fragmented, however, and there are no analyzes sufficiently refined to capture the problem's complex physics. Although the literature reported few studies on the problem (Arfaie et al., 2018; Christy et al., 2014; Han et al., 2018; E Keramaris & Pechlivanidis, 2016; Li et al., 2015; Navaratnam, 2018; Pivem & Lemos, 2013; Purkait et al., 2017).

Open channel studies with bare banks and coarse beds show that the accelerating flow suppresses turbulence generation, while the decelerating flow has the opposite effect (Houra et al., 2000). Some research has been done to study the effect of non-uniformity on the distribution of velocity and turbulence characteristics of open channel flow with bare banks.

Afzalimehr et al. (2012) stated that Cardoso et al. (1991) studied gradually accelerated flows in a smooth channel and concluded that the velocity distribution cannot be represented for the total flow depth by the universal log-law except at regions very close to the bed y/h<0.2, where y is distance from the bed and *h* is the total flow depth. Studies by Song and Graf (1994), Kironoto and Graf (1995), Song and Chiew (2001) stated that the velocity profiles, turbulence intensities and Reynolds stress distributions for both accelerating and decelerating flows in gravel-bed channel and comes with conclusions that:

i. the maximum velocity occurs below the water surface for accelerating flow and at the water surface for decelerating flow.
ii. the standard log-law velocity profile works well for *y/h*<0.2 for accelerating and decelerating flows.
iii. Reynolds stress and turbulence intensities distributions for accelerating flow are concave and for decelerating flow are convex.
iv. The wake function works well under accelerating and decelerating flows.

Mendoza and Zhou, 1992(a) stated that the rough and permeable boundary flows double the role of bed porosity. Instead, it allows the flow through the porous medium when a pressure gradient is applied, but it also leads to a complex interaction between the turbulent flow above the bed and the flow below which leads to a finite slip velocity U_0 on the surface of the porous bed, which invalidates the usually applicable no - slip condition at the flow boundary. This process has resulted in fundamental flow characteristics changes.

Keramaris, E., and Prinos, P. (2009) experimentally investigated the turbulent flow in an open channel with permeable bed. The permeable bed was initially simulated with porous filters and then the vegetation was flexible. Measurements of mean velocity and turbulent characteristics (Reynold stresses) reveal the effect on the flow characteristics of the material used (filters and vegetation).

Pechlivanidis et al. (2012) used a PIV to experiment with the turbulent characteristics of open - channel flow. Results showed that speed over the vegetation region depends on vegetation height and overall flow depth; velocity decreases with increasing vegetation height. In addition, the authors showed that velocity above the vegetation area were lower than velocity above impermeable bed. This is due to turbulent shear stress and turbulence in the area of vegetation, reducing the mean velocity above the area of vegetation.

2.7 Hydraulic roughness

For Manning's equation, Equation 2.2, which includes the friction factor (f) and Manning's n, respectively, as hydraulic roughness coefficients, open channel discharge equations include the Darcy - Weisbach equation Equation 2.1.

$$V = \sqrt{\frac{8g}{f}}\sqrt{RS} \qquad 2.1$$

$$V = \frac{Kn}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad 2.2$$

Where,

V = mean velocity (m/s)

g = acceleration due to gravity (m/s^2)

K_n = 1.0 (SI) units

R = hydraulic radius (m)

A = cross sectional area (m^2)

P = wetted perimeter (m)

R = D/4 for a pipe of diameter D,

S = channel of slope

Manning's equation has been applied to open channel calculations continuously and with great popularity because n is thought to be an absolute coefficient of roughness, depending only on the roughness of the surface. Faruque and Balachandar's main findings (2010) show a 200% to 300% decrease or increase in the magnitude of the different velocity triple products between smooth and rough beds. This shows that roughness has a significant impact on the transportation of turbulent kinetic energy and shear stress from Reynolds.

It is seen that the effect of bed roughness has penetrated most of the flow depth, challenging the conventional hypothesis of "wall similarity." The results show that the maximum roughness effect is generated by the distributed roughness. The differences in the characteristics noted by the triple velocity products exceed 200 percent between the smooth and rough bed flow.

Tachie et al. (2004) noted that surface roughness significantly enhances turbulence kinetic energy and turbulence diffusion levels in a way that depends on the specific roughness element geometry. The existing literature indicates that there are conflicting opinions among researchers on the extent of the effect on turbulence characteristics of bed roughness and aspect ratio.

Raupach et al. (1991), suggesting that the turbulent mixing properties in smooth and rough walls should be essentially the same outside of the roughness layer. The effect of roughness on the mean velocity profile is apparent through most flow depth with the distributed roughness showing the greatest deviation from the smooth profile. For the lower Reynolds, natural sand bed shows a greater deviation than continuous roughness.

2.7.1 Darcy- Weisbach

At relatively high Re, f becomes independent of Re and is solely dependent on R and k. f decreased with increasing Re, with the minimum f values bounded by an equation in the form of Equation 2.3, where f is a function of Re and the coefficients a and b are boundary roughness (k) specific.

$$\frac{1}{\sqrt{f}} = a \log\left(\frac{Re\sqrt{f}}{b}\right) \qquad 2.3$$

Where; a , b = empirical coefficients specific for a given channel shape and boundary roughness.

Prandtl developed an equation (commonly referred to as the equation of Prandtl-von Kármán) in the form of Equation 2.3, which describes f data for smooth walled pipe with a and b equal to 2 and 2.51, respectively (Crowe et al. 2001). The data presented by Chow (1959) on open channel flow stage-discharge suggest that a and b will vary with the type of boundary roughness, such as increasing f values with increasing boundary roughness or increasing k values.

Chow (1959) also suggests that a quasismooth flow condition exists when the behavior of f for a given boundary roughness material can be described with a constant set of empirical coefficients (a and b) by Equation 2.3. Morris (1955) introduced the idea of a quasi-smooth boundary flow condition and describes a flow state where the areas between the roughness elements are filled with stable eddies, creating a smooth wall-like pseudo-wall flow boundary (Figure 2.7). The results of this study confirm that Equation 2.3 is a relative limiting boundary to f and also show that this limiting boundary is relevant to a constant n assumption.

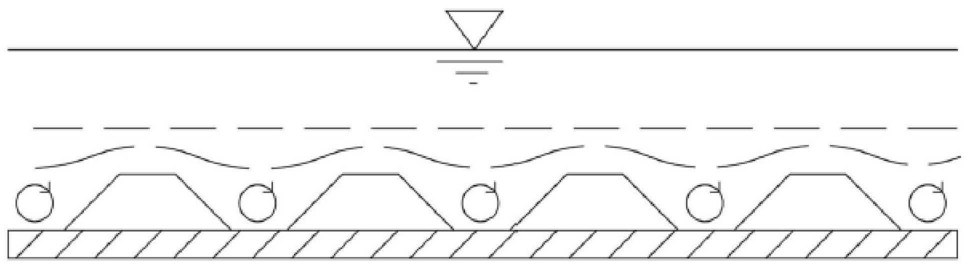

Figure 2.7: Illustration of the quasi-smooth flow boundary theory

2.7.2 Manning, n Coefficient, n

Equation 2.4 relates the Manning's *n* roughness coefficient

$$\frac{V}{V*} = \sqrt{\frac{8}{f}} = \frac{K_n R_h^{1/6}}{n\sqrt{g}} \quad 2.4$$